Environmental variation also amplifies genotype×environment (G×E) interactions, leading to unstable performance of high-yield and high-sugar genotypes across regions, years, and ratoon cycles. Improvements in sugar content are generally smaller than those in biomass and are less responsive to environmental improvements, making it more difficult to maintain stable sugar levels across different ecological conditions (Amaresh et al., 2025). With increasing climate variability, factors such as drought, heat waves, extreme rainfall, and pest pressures are expected to further exacerbate instability. Therefore, multi-environment trials, environment-specific ideotype design, and refined environmental characterization are essential for improving the stability of yield and sugar content (Mehdi et al., 2024).

5.3 Breeding challenges arising from complex genetic backgrounds

The highly complex genetic background of cultivated sugarcane is another major constraint on the coordinated improvement of yield and sugar content. Modern sugarcane is a highly polyploid, aneuploid interspecific hybrid with a large genome, high heterozygosity, and complex homologous chromosome composition (Kumar et al., 2024; Wang et al., 2024; Amaresh et al., 2025). Most commercial cultivars derive the majority of their genome from *S. officinarum*, with a relatively smaller contribution from *S. spontaneum*. While this composition helps maintain high sugar traits, it also results in a relatively narrow genetic base, limited available variation, and reduced adaptive potential (Lu et al., 2024).

This complex genetic structure means that most economically important traits in sugarcane are not controlled by single major genes but by numerous small-effect QTLs, accompanied by allele dosage effects and complex interactions (Kumar et al., 2024). For traits such as high biomass and high sucrose accumulation, which may involve inherent trade-offs, combining sufficient favorable alleles within a single genotype is inherently slow and stochastic. In addition, the long breeding cycle of sugarcane, typically 10-15 years and largely reliant on clonal selection, further reduces the efficiency of improving complex traits (Amaresh et al., 2025).

Moreover, reproductive biology and quantitative genetic characteristics further complicate breeding. Asynchronous flowering, partial sterility, and limited effective crosses reduce recombination opportunities and hinder the rapid accumulation of favorable alleles. At the same time, early-stage phenotypic evaluation of yield and sugar content is highly influenced by environmental factors, reducing selection accuracy. These traits often exhibit low narrow-sense heritability and strong non-additive genetic effects, limiting the effectiveness of traditional marker-assisted selection (MAS). Although advances in reference genomes, high-density SNP platforms, and high-throughput sequencing have accelerated molecular breeding, challenges remain in accurate genotyping, allele dosage modeling, and integration of high-quality phenotypic data in polyploid contexts (Amaresh et al., 2025).

6 Breeding Strategies for the Coordinated Improvement of High Yield and High Sugar in Sugarcane

6.1 Conventional hybrid breeding and parental optimization strategies

Conventional hybrid breeding remains the core approach for sugarcane improvement, and most widely cultivated varieties are derived from this system. The basic process includes parental selection, artificial crossing, seedling population establishment, and multi-stage clonal selection and regional trials over 1014 years. In early generations, selection focuses mainly on yield-related traits such as tillering, stalk number, and vigor, while in later stages, greater emphasis is placed on sugar content, maturity, and resistance. Long-term practice shows that although this system can continuously increase yield, the gains mainly come from biomass improvement rather than significant increases in sugar content, reflecting its limitations in achieving coordinated high yield-high sugar improvement (Figure 4).

Under the goal of coordinated improvement, optimizing parental combinations becomes critical. High-biomass genotypes typically exhibit strong stalk growth, whereas high-sugar genotypes excel in sucrose accumulation and quality. Hybridizing these types can expand recombination variation in progeny. However, relying solely on empirical parental selection is inefficient; current approaches increasingly emphasize scientifically guided design based on genetic background, trait complementarity, and combining ability. Studies have shown that specific